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Iodine-frequency-stabilized AlGaInP-based VECSEL at 689 nm

Charlotte A. Hodges[1,*], Paulo Hisao Moriya[1], Jennifer E. Hastie[1]

[1]*Institute of Photonics, Department of Physics, SUPA, University of Strathclyde, 99 George Street, Glasgow, G1 1RD, United Kingdom.*

**Corresponding author:charlotte.hodges@strath.ac.uk*

Abstract: We demonstrate a high-brightness, iodine-locked AlGaInP-based VECSEL at 689 nm with estimated linewidth of 6.6(5) kHz and reduced frequency drift, targeting neutral Sr-based timing applications.

1. Introduction

The low noise, narrow linewidth performance of frequency-stabilized lasers is prerequisite in applications where narrow or ultra-narrow atomic transitions are utilized. An example is the neutral strontium (Sr) optical clock, where the $^1S_0 \rightarrow {}^3P_1$ transition at 689 nm is used as the second-stage laser cooling transition. Current systems targeting this transition are based on external cavity diode lasers (ECDLs) that are stabilized to high-finesse Fabry-Perot cavities to achieve linewidth requirements [1], but that incur cooling efficiency losses due to cavity drift caused by thermal fluctuations and vibrations. To minimize this instability, an absolute spectral referencing element can be introduced, which is most reliably done with spectroscopy of the atomic species of interest, but this increases the laser brightness demands. Unfortunately, Sr spectroscopy of *red* cooling transitions (as opposed to blue) comes with further challenges. Firstly, to facilitate adequate interactions with red light, the spectroscopy cell should be long (>50 cm) and be kept at temperatures exceeding 400 °C [2]. Secondly, Sr atoms readily adsorb to glass, giving reference cells a limited lifetime despite compensatory measures. Despite recent developments (see, e.g. [3]), Sr cell architectures remain impractical for the 689 nm transition, so other references may be considered. Molecular alternatives, such as iodine, are widely available, offering a wide range of transitions at different wavelengths in progressively more compact cell embodiments. Here we exploit the advantages of vertical-external-cavity surface-emitting-laser (VECSEL) technology [4] - namely high-brightness, low noise performance with narrow free-running and intrinsic linewidths - to observe, and *directly* lock to, sub-Doppler signals of molecular iodine around 689 nm, achieving output powers above 100 mW, an integrated linewidth of 6.6(5) kHz, below that of the $^1S_0 \rightarrow {}^3P_1$ Sr transition, without any additional frequency stabilization, and an order-of-magnitude reduction in frequency drift compared with locking to a compact commercial reference cavity.

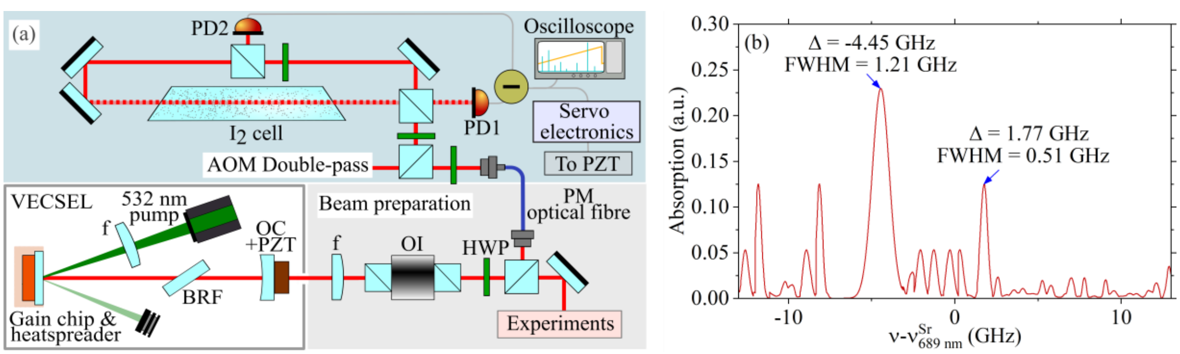

Fig. 1: (a) VECSEL and spectroscopy setup schematics, connected by a polarization maintaining (PM) fiber. In the latter, light is modulated by an acousto-optic modulator (AOM), in a double pass configuration, before the iodine cell; balanced photodetectors PD1 and PD2 monitor the probe and pump signals, respectively. Other elements: half waveplate (HWP), optical isolator (OI), lens (f), birefringent filter (BRF), output coupler (OC), piezo-electric transducer (PZT). (b) Sub-Doppler spectrum of molecular iodine close to the $^1S_0 \rightarrow {}^3P_1$ transition at 689 nm. Blue arrows indicate candidate locking peaks. Detuning, Δ, from the $^1S_0 \rightarrow {}^3P_1$ transition and full-width half-maximum (FWHM) are indicated.

2. Experimental set-up

The VECSEL and spectroscopy set-up is shown in Fig. 1a. The monolithic VECSEL gain chip is identical to that reported in [5], consisting of an AlGaAs/AlAs distributed Bragg reflector (DBR) and 10 pairs of GaInP quantum wells (QWs) designed for emission at 689 nm when pumped at 532 nm (Coherent VERDI G). (We note that blue or green diode-pumping of these gain structures is also feasible, as shown in previous work, e.g. [6]). A diamond heatspreader is capillary bonded to the gain chip surface, and the resulting composite is then mounted in a thermo-electrically controlled brass mount. The two-mirror VECSEL cavity is formed with a 2% transmission plano-concave output coupling mirror (radius-of-curvature = 100 mm), mounted on a piezo-electric transducer (PZT) for locking purposes. The cavity mode and pump spot sizes both have a diameter of 90μm. Electronic coarse and fine wavelength tuning are performed by temperature control of the intracavity birefringent filter (BRF) and gain chip, respectively. To minimize the effects of environmental noise, the VECSEL is mounted within a closed metal box. To perform sub-Doppler spectroscopy a co-linear saturated absorption configuration was used (see Fig. 1a). The commercial 19-cm iodine cell (GC19100-I, Thorlabs) was maintained at temperatures up to 55 °C (cold finger at room temperature). The spectroscopy locking signal was sent back to the VECSEL PZT via servo electronics. For comparison, frequency stabilization to an air-spaced Fabry-Perot reference cavity (finesse = 1k, free-spectral range = 300 MHz) via Pound-Drever-Hall (PDH) was also performed. The spectroscopy and PDH stabilization stages are referred to, respectively, as the iodine lock and cavity lock. The iodine lock used approximately 50-60 mW, and the cavity lock 10 mW, of VECSEL output power, leaving up to 60 mW or 110 mW available for experiments, respectively.

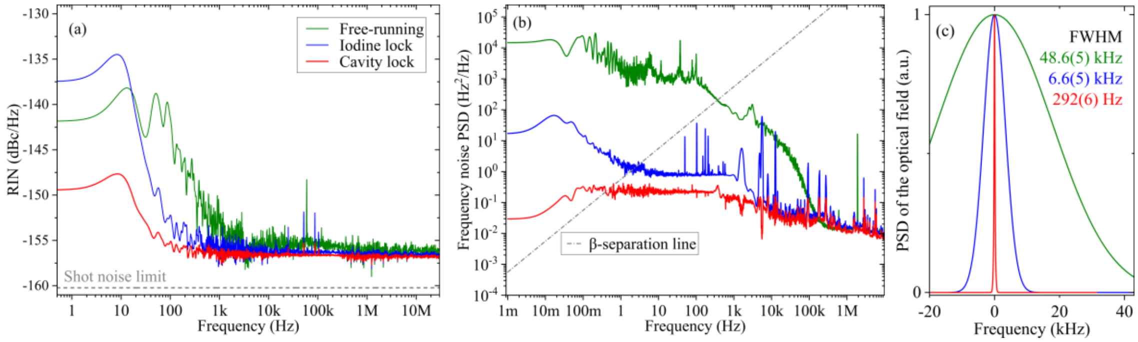

Fig. 2. (a) Relative intensity noise (RIN) of the VECSEL when free-running (green trace), locked to an iodine absorption feature (blue), or locked via PDH to a reference cavity (red). (b) Frequency noise power spectral density (FNPSD) for all three cases, using 100 s acquisition time. (c) Optical field PSD generated via autocorrelation. FWHM values are indicated.

3. Results and discussion

The sub-Doppler iodine absorption spectrum is shown in Fig. 1b. Two iodine absorption features of interest were found within the AOM scanning range of ±30 GHz, detuned by -4.45 and +1.77 GHz from the $^1S_0 \rightarrow {}^3P_1$ transition of Sr, with the stronger red-detuned transition used for locking. The free-running, iodine- and cavity-locked VECSEL noise and linewidth performance are shown in Fig. 2. In Fig. 2a, comparison with the free-running case shows a clear reduction in relative intensity noise (RIN) for the iodine-locked VECSEL at frequencies above 60 Hz, with the RIN reaching a minimum value < -156 dBc/Hz for f > 10 kHz in all cases. In terms of frequency noise (see Fig. 2b), a similar scenario is observed. Locking the VECSEL to iodine significantly reduces the frequency noise contribution above the β-separation line [7], resulting in narrower Gaussian linewidths, which can be confirmed by estimating the VECSEL linewidth via auto-correlation and the Wiener-Khintchine theorem [7]. Here, the free-running VECSEL linewidth of 48.6(5) kHz is reduced to 6.6(5) kHz when locked directly to iodine. Further improvements in the overall setup to improve the signal-to-noise ratio and resolution of the iodine absorption features closer to the $^1S_0 \rightarrow {}^3P_1$ Sr transition, such as more compact cells, reduction of environmental noise and more stable VECSEL embodiments [6], can be implemented to reduce even further the spectral width towards, and even below, the cavity-locked linewidth of 290(6) Hz, and with reduced detuning. Importantly, however, an improvement in frequency stability of more than an order of magnitude is observed with the iodine lock compared with the cavity lock under the same laboratory conditions, leading to a reduction of the drift from 3.89 kHz to 145 Hz, over a time span of 20 min, as measured with a wavelength meter (HighFinesse WS7-30).

4. Conclusions

We have directly locked a high-brightness AlGaInP-based VECSEL to a molecular iodine transition at around 689 nm to demonstrate low noise operation with an estimated linewidth of 6.6(5) kHz, narrower than the spectral width of the neutral Sr red cooling transition, with reduced frequency drift when compared to cavity-stabilized VECSEL. This first demonstration of iodine locking at these wavelengths opens the possibility to explore even further the advantages of VECSEL technology with more compact spectroscopy cell geometries to create miniaturized, low-drift referencing solutions for high performance narrow-linewidth lasers. Work is underway to achieve locking to those iodine absorption features closer to the $^1S_0 \rightarrow {}^3P_1$ Sr cooling transition frequency to reduce the requirement for offset locking for applications such as optical clocks.

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References

[1] N. Poli et al., "Laser sources for precision spectroscopy on atomic strontium", Spectrochim. Acta A: Mol. Biomol. Spectrosc. 63, 981 (2006).
[2] I. Manai et al., "Shelving spectroscopy of the strontium intercombination line". J. Phys. B At. Mol. Opt. Phys. 53, 085005 (2020).
[3] J. M. Pate et al., "Microfabricated strontium atomic vapor cells". Opt. Lett. 48 (2), 383 (2023).
[4] M. Guina et al., "Optically pumped VECSELs: review of technology and progress". J. Phys. D: Appl. Phys. 50, 383001 (2017).
[5] P.H. Moriya et al., "Sub-kHz-linewidth VECSELs for cold atom experiments". Opt. Express 28, 15943 (2020).
[6] P.H. Moriya et al., "Sub-kHz linewidth free-running monolithic cavity VECSEL with 10^{-12} stability", Optica Open, 25480285 (2024).
[7] G. Di Domenico et al., "Simple approach to the relation between laser frequency noise and laser line shape". Appl. Opt. 49 (25), 4801 (2010).